System Strength Impact Assessment Guideline Withstand SCR Methodology Review

August 2024

Technical note on assessing power transfer limits

Version 1.1

Important notice

Purpose

AEMO has prepared this document to understand the limitations of the current System Strength Impact Assessment Guidelines (SSIAG) test methodology for assessing the withstand short circuit ratio (SCR). Clarifications and adjustments have been proposed to ensure that the methodology does not prescribe test conditions for plant that result in a breach of active power transfer limits in weak grid conditions.

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Version control

Version	Release date	Changes
#1.0	02/07/2024	Initial draft
#1.1	23/08/2024	Editorial updates

AEMO acknowledges the Traditional Owners of country throughout Australia and recognises their continuing connection to land, waters and culture. We pay respect to Elders past and present.

Abbreviations

Abbreviation	Term
3PHG	Three-phase to ground
AEMO	Australian Energy Market Operator
AFL	Available Fault Level
BESS	battery energy storage system
EMTDC™	electromagnetic transient including DC
GFL	Grid-following
GFM	Grid-forming
IBL	Inverter-based load
IBR	Inverter-based resource/s
OEM	original equipment manufacturer
MVA	megavolt ampere/s
MVAr	megavolt ampere/s reactive
MW	megawatt/s
NEM	National Electricity Market
NER	National Electricity Rules
NSP	network service provider
OEM	original equipment manufacturer
PSCAD™	Power System Computer Aided Design
PSS®E	Power System Simulator for Engineering
pu	per unit
SCR	short circuit ratio
SMIB	Single Machine Infinite Bus
SSC	System Strength Charge
SSIAG	System Strength Impact Assessment Guidelines
SSQ	System Strength Quantity

Executive summary

The System Strength Impact Assessment Guidelines (SSIAG[1]) introduced new concepts and methodology to evaluate the impact of inverter-based resource (IBR) generators and loads on the system. AEMO is required to publish the SSIAG under National Electricity Rules (NER) 4.6.6 which includes a requirement to provide a methodology for assessing the short circuit ratio (SCR) to determine whether a connecting plant complies with the SCR access standards[2].

The minimum set of Withstand SCR tests for a 4.6.6 Connection is specified in Appendix B of the SSIAG. The tests are intended to assess the plant's capability to ride through low SCR scenarios (down to an SCR of 1.2 as defined by the stability coefficient constant value). This assessment must take into account power transfer limits at the connection point, as required by the acceptance criteria in SSIAG sections 7.4.4 (h) and (i). As currently defined, the tests do not contemplate active power absorption by connecting plant. This represents a gap in the current SSIAG methodology which results in plant being incapable of simultaneously satisfying the requirements of the acceptance criteria in sections 7.4.4 (h) and (i) while operating at full rated charging levels as required by section 7.4.3 (d).

This document focuses on clarifying and adjusting the Withstand SCR tests to accommodate conditions where connecting plant is absorbing active power without breaching power transfer limits at the connection point, with the aim of giving effect to the intent of the current SSIAG methodology when applied to power absorbing plant.

In this review, AEMO proposes clarifications and adjustments to the Withstand SCR test methodology, for scenarios where the power transfer limits are breached or are likely to be breached. These clarifications and adjustments are based on static stability theory, that applies irrespectively to the plant mode of control (for example, grid-following or grid-forming).

The analysis presented in this technical note indicates that, for a given SCR, the power transfer limit that applies when the plant is in absorbing mode is more onerous than when the plant is in injection mode. As it stands, it is not possible for plant absorbing active power from the network (including grid-forming BESS) to achieve a withstand SCR of 1.2 when absorbing at its maximum rated power, because the methodology leads to a violation of power transfer limits. The recommendations are:

- **All plant** – AEMO proposes clarifying and adjusting the SSIAG methodology to define the infinite bus voltage range instead of the fixed reactive power and voltage values at the plant connection point. The recommendation is to set the infinite bus voltage within the range of 1.00 pu and 1.05 pu, but as close as possible to 1.00 pu.
- **Bi-directional plant operating in active power absorption mode (BESS, variable speed pumped hydro or hybrid plants)** – AEMO proposes clarifying and adjusting the SSIAG methodology to reduce the maximum active power flow, to avoid breaching power transfer limits at the connection point, based on the site-specific SCR and X/R ratio.

[1] AEMO, *System Strength Impact Assessment Guidelines*, Version 2.2, 28 June 2024, at https://aemo.com.au/-/media/files/stakeholder_consultation/consultations/nem-consultations/2024/ssiag/system-strength-impact-assessment-guidelines-v22.pdf.

[2] NER S5.2.5.15, S5.3.11 and S5.3a.7.

- **Inverter-based load (IBL)** – AEMO recognises similar issues exist for IBL, and proposes this be treated separately in future work, as the industry is still building its knowledge and experience with IBL technology. AEMO's review of technical requirements[3] proposes a detailed review of large loads, planned to commence in the second half of 2024[4].

Background

Section 7.4 of the SSIAG outlines how the SCR (referred to as Withstand SCR in the SSIAG) is to be assessed through dynamic simulation studies in a Single Machine Infinite Bus (SMIB) environment using site-specific Power System Computer Aided Design (PSCAD™)/electromagnetic transient including DC (EMTDC™) and Power System Simulator for Engineering (PSS®E) models.

The resultant Withstand SCR is used in determining the reduction in Available Fault Level (AFL)[5] caused by the connection of plant at its connection point, and to calculate the System Strength Quantity (SSQ)[6].

The published methodology for assessing the Withstand SCR takes into consideration the network conditions at the plant connection point and the technology of the plant being connected to define the acceptance criteria that should be applied.

The minimum set of tests to be carried out is described in Appendix B of the SSIAG. These tests require the plant to ride through three-phase to ground (3PHG) faults, impulse voltage steps and changes in network impedances with the network impedances varying from an equivalent SCR of 10 down to withstand SCR, irrespective of the plant's control mode (grid-following or grid-forming). Currently, Withstand SCR test requirements do not specify the infinite bus voltage and the active power absorption level for bidirectional plants.

Summary and way forward

The minimum withstand SCR tests as they stand in the current SSIAG make it impossible for any plant, which absorbs active power from the network, to achieve a withstand SCR of 1.2 at maximum power absorption due to a violation of power transfer limits at the connection point.

To demonstrate the power transfer limits under conditions where plant is absorbing active power, AEMO has used static stability theory. This theory is introduced in Section 1 of the technical note, and is the foundation of the static analysis in Section 2. It is important to highlight that from a static stability perspective, the technology or the control mode of the plant has no particular significance and any comparison of the dynamic stability of the grid-forming and grid-following technology is beyond the intent of this technical note.

The static stability limits have been verified through dynamic simulations performed in PSCAD™ (see Section 2), with recommendations outlined in Section 4. Key recommendations are to limit the plant's active power absorption in low SCR conditions based on the X/R ratio, and define the voltage of the infinite bus of the test network for the Withstand SCR tests rather than specify the reactive power and voltage values at the connection point.

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[3] See https://aemo.com.au/consultations/current-and-closed-consultations/aemo-review-of-technical-requirements-for-connection.

[4] AEMO, *Review of technical requirements for connection final report*, 22 December 2023, Section 4.10, at https://aemo.com.au/-/media/files/stakeholder_consultation/consultations/nem-consultations/2022/aemo-review-of-technical-requirements-for-connection-ner-clause-526a/final-report_access-standards-review_final_.pdf.

[5] SSIAG Section 3.4

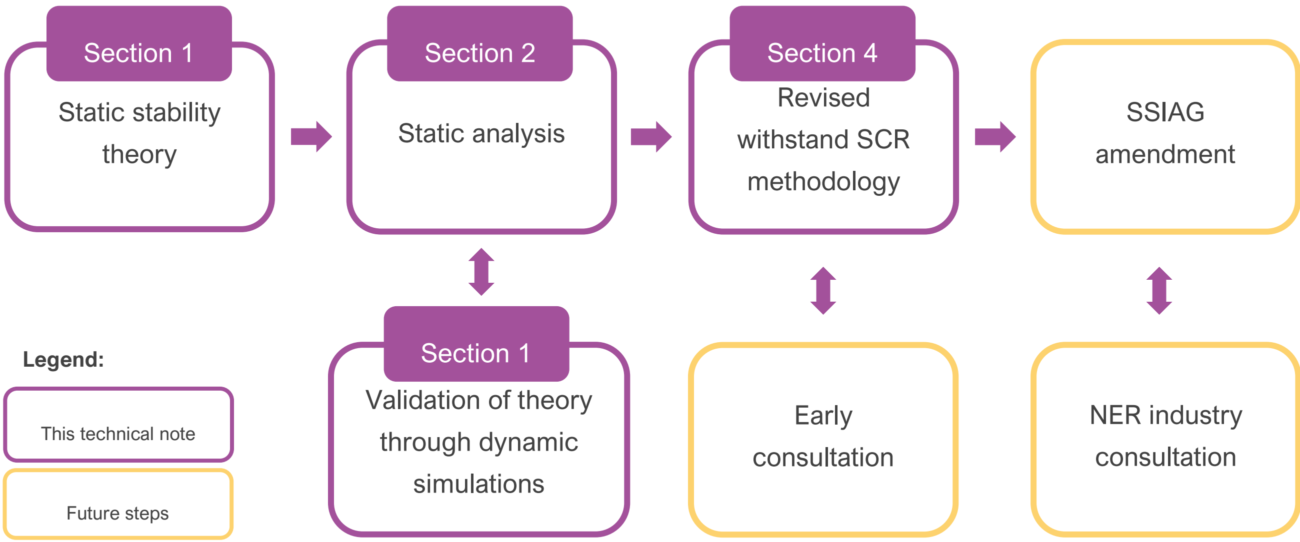
[6] NER 6A.23.5

Figure 1 summarises the structure of this report and also sets out the proposed next steps to validate and implement the recommendations (in yellow). These next steps include early consultation with network service providers (NSPs) and industry stakeholders that have experienced the issue in the past, followed by broader industry consultation in line with the rules consultation procedures[7] to amend and publish an updated version of the SSIAG.

In the absence of clear guidance in the current SSIAG on the appropriate methodology to apply to plant that absorbs active power, AEMO encourages NSPs to consider adopting the principles of the methodology proposed in this technical note. This will assist in developing a consistent methodology across the NEM as compared with the variety of approaches which have been employed to date and will inform ongoing work to review and refine the SSIAG methodology in advance of future amendments to the SSIAG planned to commence in Q1 2025.

AEMO is working towards expanding on the proposed principles to establish detailed guidance on specific tests. An updated technical note is planned to be published in November 2024.

Figure 1 Technical note structure and way forward



[7] NER 8.9

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1 Introduction

The System Strength Impact Assessment Guidelines (SSIAG[8]) introduced new concepts and methodology to evaluate the impact of inverter-based resource (IBR) generators and loads on the system.

As part of the SSIAG, AEMO is tasked under the National Electricity Rules (NER) 4.6.6 to provide a methodology:

- To be used by network service providers (NSPs) for undertaking system strength impact assessments, and
- For assessing the short circuit ratio (SCR) to determine whether a connecting plant complies with the SCR access standards[9].

The Withstand SCR test cases for a 4.6.6 Connection are specified in Appendix B of the SSIAG. The tests are intended to assess the plant's capability to ride through low SCR scenarios, taking into account transfer stability limits according to the acceptance criteria in SSIAG sections 7.4.4 (h) and (i).

The Withstand SCR test cases contain three types of tests – three-phase to ground (3PHG) faults, voltage step changes, and impedance changes. The issues that are identified in relation to the tests are:

- For a given SCR, the power transfer limit that applies when the plant is in absorbing mode is more onerous than when the plant is in injection mode.
- Large initial positive reactive power injection from the plant is also necessary for the plant to absorb active power in weak grids.

In addition to the points listed above, and irrespective of whether the plant is generating or absorbing active power, the source voltage in the Single Machine Infinite Bus (SMIB) network is not specified for the SSIAG Appendix B test cases. It is, however, considered to be critical in determining the Withstand SCR.

The following section introduces the static stability theory that defines how much active power can be absorbed by inverter-based load (IBL), variable speed pumped hydro plants when in pumping mode and battery energy storage systems (BESS) when in charging mode. The theory is fundamental for the static case studies and analysis outlined in Section 2, demonstrating the influence of the SCR and X/R ratio on the power transfer limits.

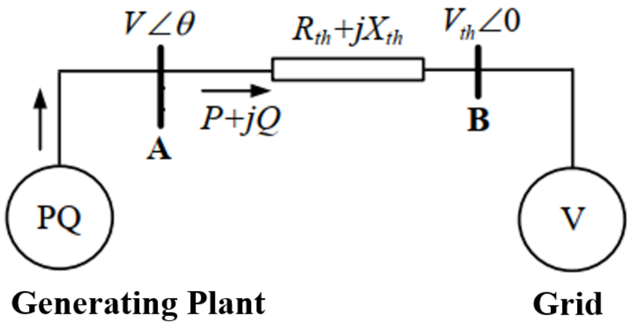
1.1 Static stability theory

The static stability theory is presented in a simplified two-bus system as shown in Figure 2, where the Generating Plant at Bus A is connected to Bus B (the infinite bus, voltage source) via an impedance of $R_{th}+jX_{th}$.

[8] AEMO, System Strength Impact Assessment Guidelines, Version 2.2, 28 June 2024, at https://aemo.com.au/-/media/files/stakeholder_consultation/consultations/nem-consultations/2024/ssiag/system-strength-impact-assessment-guidelines-v22.pdf.

[9] NER S5.2.5.15, S5.3.11 and S5.3a.7

Figure 2 2-bus system for the static stability study



Equations (1) to (5)[10, 11] determine the *loci* for valid load flow solutions:

$$P = \alpha(V^2 - VV_{th}\cos\theta) + \beta VV_{th}\sin\theta \quad (1)$$

$$Q = \beta(V^2 - VV_{th}\cos\theta) - \alpha VV_{th}\sin\theta \quad (2)$$

where

$$\alpha = \frac{R_{th}}{|Z_{th}|^2} \quad (3)$$

$$\beta = \frac{X_{th}}{|Z_{th}|^2} \quad (4)$$

$$Z_{th} = \sqrt{R_{th}^2 + X_{th}^2} \quad (5)$$

If the grid impedance $R_{th}+jX_{th}$ is specified through a grid SCR and X/R ratio, then they can be calculated from Equation (6) to (8).

$$|Z_{th}| = \frac{1}{(SCR)} \quad (6)$$

$$R_{th} = \frac{|Z_{th}|}{\sqrt{1 + (XRR)^2}} \quad (7)$$

$$X_{th} = (XRR)R_{th} \quad (8)$$

[10] T. Lund, H. W., etc, *Operating Wind Power Plants Under Weak Grid Conditions Considering Voltage Stability Constraints.* IEEE Transactions on Power Electronics, vol. 37, no. 12, pp. 15482-15492, Dec 2022.

[11] A. Borićič, J. L. R. Torres and M. Popov, "Beyond SCR in Weak Grids: Analytical Evaluation of Voltage Stability and Excess System Strength," 2023 International Conference on Future Energy Solutions (FES), Vaasa, Finland, 2023, pp. 1-6, doi: 10.1109/FES57669.2023.10183286.

Equations (9) and (10) are for calculating ∂P/∂θ and ∂Q/∂V and can be derived from Equation (1) to (5).

$$\frac{\partial P}{\partial \theta} = VV_{th}(\alpha \sin\theta + \beta \cos\theta) \tag{9}$$

$$\frac{\partial Q}{\partial V} = 2\beta V - \frac{\frac{V_{th}^2 V}{|Z_{th}|^2} + 2P\alpha V - 2\alpha^2 V^3}{\sqrt{\frac{V_{th}^2 V^2}{|Z_{th}|^2} - (P^2 - 2P\alpha V^2 + \alpha^2 V^4)}} \tag{10}$$

The static stability theory requires the two-bus system to meet the ∂P/∂θ > 0 for angle stability and ∂Q/∂V > 0 for voltage stability simultaneously. It is important to note that the grid should have sufficient transfer capability to meet both ∂P/∂θ > 0 and ∂Q/∂V > 0 at the connection point under normal operating voltage, and thermal limits should also be satisfied.

In the two-machine system, the critical angle for power transfer capability is 90°[12] when considering angle stability. Note this relationship is mainly important when dealing with a two-machine system. For larger complex systems, an angular separation of 90° between two machines has no particular significance[13]. Nevertheless, both the voltage and angle stability limits define the power transfer capability, noting that voltage stability has a more significant impact than angle stability. This is demonstrated in the following sections.

1.2 Active power absorption issue

To better understand the issues with the 3PHG test methodology for conditions where a connection is absorbing power from the network (including variable speed pumped hydro pumping, BESS charging and IBL), the following basic test procedure is used:

1. Set the initial conditions at the connection point as P = -1.0 per unit (pu), Q = 0 pu and V = 1 pu
2. Set the impedance of the network to achieve SCR of 10 and X/R of 3
3. Set the network source voltage Vth = ~1.036 pu. This is the steady state source voltage for SCR of 10 and X/R ratio of 3 for the desired load flow
4. Run the model until steady state is achieved and apply a 3PHG fault with a 0.43 second fault duration
5. At fault recovery, the network impedance is adjusted to achieve SCR of 1.2 and X/R ratio of 3 post-fault
6. Run the model until a new steady state is achieved, confirming the plant ride-through capability.

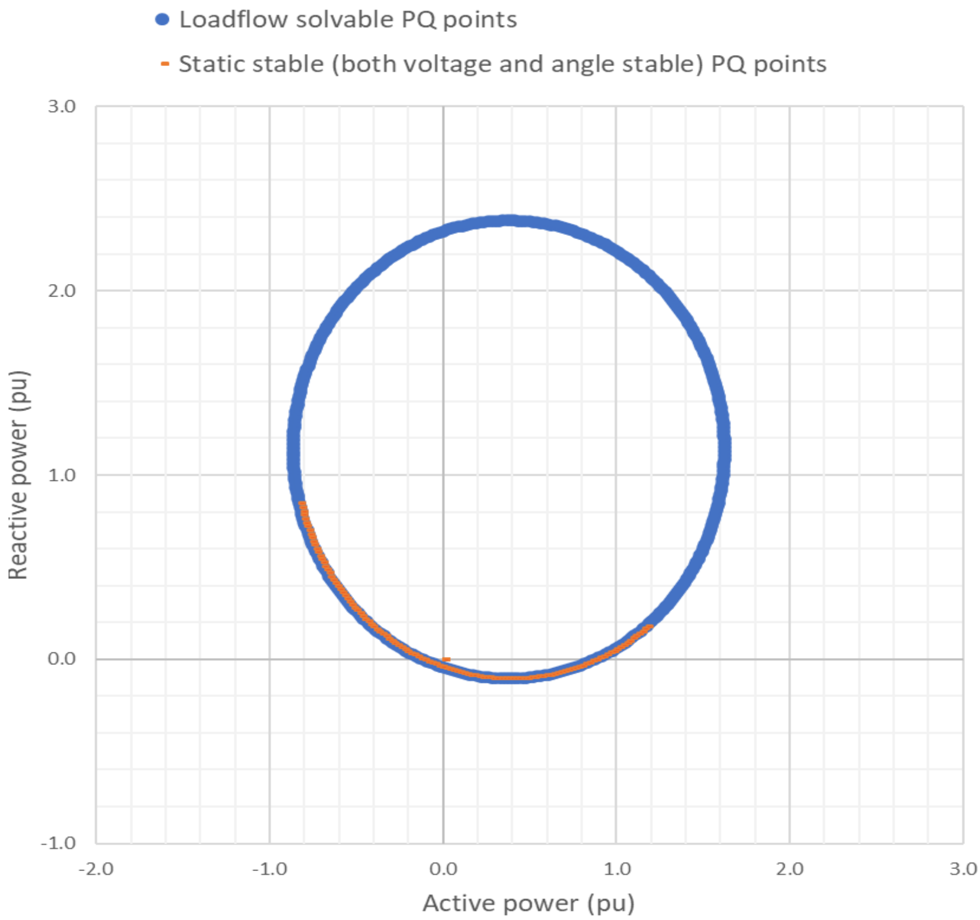
[12] The critical angle of 90° is only valid for pure reactive networks (X/R ratio >> ∞).

[13] Kundur, P. (1994), Power System Stability and Control.

Independent of the technology type, the power transfer capability limit is breached if the connection point is fully absorbing (P = -1.00 pu) active power when the SCR is reduced to 1.2. The infinity bus voltage (V_{th}) is kept at the pre-fault initial conditions, which is V_{th} = 1.036 for this example.

Figure 3 shows the load flow *loci* (in blue) and the limits of both angle and voltage stability for the conditions described above. The orange colour represents the stable active and reactive power combinations that meet both the angle stability ($\partial P/\partial \theta > 0$) and voltage stability ($\partial Q/\partial V > 0$) criteria. It shows that the maximum absorbing point (P = -1.00 pu) is unstable. It is important to highlight that a similar effect would be encountered by an IBL.

Figure 3 Load flow solution loci for SCR 1.2, X/R = 3, V = 1.0 pu and Vth = 1.036 pu



The SSIAG clearly excludes tests which fall outside of the stable operating region shown in Figure 3, as defined by the acceptance criteria described in sections 7.4.4 (h)[14] and (i)[15]. At the same time, the SSIAG requires the BESS plant (independent of grid-following or grid-forming technology) to be assessed at full rated charging in section

[14] "The 4.6.6. Connection must not trip unless the operating conditions are outside of *power system* stability limits".

[15] "The 4.6.6. Connection must not continue indefinitely in FRT mode unless the operating conditions are outside of *power system* stability limits".

7.4.3 (d)[16]. These two requirements are conflicting, thereby making it impossible for the plant to satisfy both at the same time in low SCR conditions (for example, SCR of 1.2).

For a specific active power absorption case, Figure 3 presents the power transfer limits. To provide a generic assessment that considers various grid SCR and X/R ratio conditions the static analysis is provided in Section 2.

[16] "…for 4.6.6 Connections comprised of BESS, regardless of whether they are grid-forming or grid-following, all assessments must be conducted at full rated charging and discharging levels up to the maximum registered (or proposed) capacity, including at STATCOM operation (i.e. at zero active power output)".

2 Static analysis

Based on the static stability theory, this section presents case studies exploring the limits of power transfer capability under low SCR and active power absorption conditions. The two static case studies presented below consider unlimited and limited plant reactive power capability and do not distinguish between any particular technology. In the applied case methodology, the connection point voltage of the plant is fixed at levels within the normal operating range, hence the representation of the static stability results differs from the classical QV and PV curve methods, instead using the ∂P/∂θ and ∂Q/∂V representation introduced in Section 1.1.

2.1 Unlimited plant reactive power to keep plant voltage at 1.0 pu

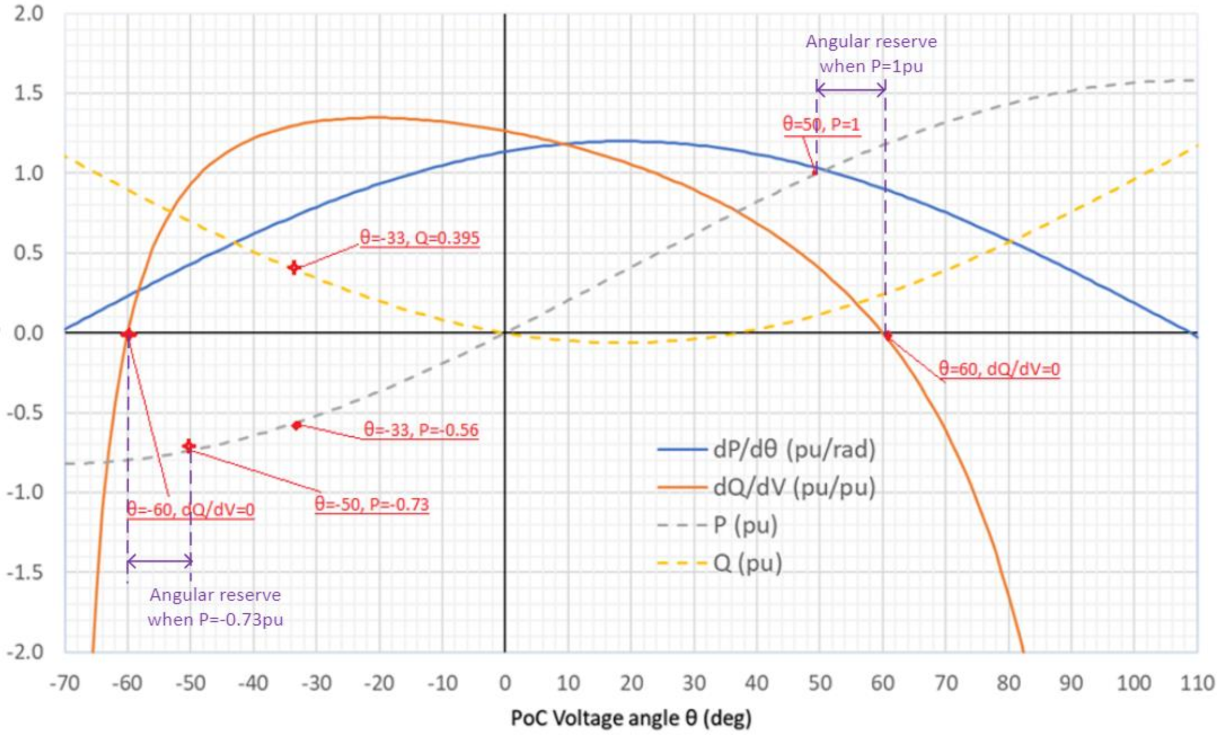
This case is used to demonstrate the transfer capability of a theoretical plant with unlimited reactive power capability. The system is assumed to be a two-bus system, where positive P means the plant is generating:

- The base capacity for SCR and per unit calculation is P_{Rated} (MW), which is the plant rated capacity at the point of connection
- The grid SCR is 1.2 and the X/R ratio is 3
- The voltage of Bus A and Bus B are both at 1.0 pu.

Figure 4 presents ∂P/∂θ, ∂Q/∂V, P and Q against Bus A voltage angle θ (relative to infinite bus) of the case with conditions detailed above. The key observations to highlight from Figure 4 are:

1. Voltage stability has a stricter requirement than angle stability
   - θ range is -59° to 59° for ∂Q/∂V > 0, while it is -70° to 108° for ∂P/∂θ > 0
   - P range is -0.79 pu to 1.16 pu for ∂Q/∂V > 0, while it is -0.82 pu to 1.58 pu for ∂P/∂θ > 0
2. Loads (negative P) have a smaller active power stability limit (in absolute value) than generators (positive P), in two ways
   - P stability limit is -0.79 pu for loading, comparing to the 1.16 pu limit for generating
   - ∂Q/∂V decreases faster in loading than in generating when P approaches the limits
3. When the plant is generating 1.0 pu active power, the angular reserve is approximately 10°
4. If a 10° angular reserve is applied to the plant when it is absorbing active power, the plant cannot absorb more than 0.73 pu active power (i.e., P = -0.73 pu is the limit)
   - Note that the plant is required to send out 0.69 pu reactive power to support the plant staying at 1.00 pu voltage when P = -0.73 pu
5. If the plant reactive power is limited to 0.395 pu, to maintain 1.0 pu voltage at the plant, the maximum active power that the plant can absorb is 0.56 pu (that is, the operating point left limit in Figure 4 is at θ = - 33° where P = -0.56 pu).

Figure 4 Static stability check on a 2-bus system (SCR = 1.2, X/R = 3, Vth = 1.0 pu, and V = 1.0 pu)



2.2 Limited plant reactive power at ±0.395 pu

The following analysis takes into consideration the limits for the Automatic Access Standard reactive power requirement[17] and the operational voltages in the network. If the following assumption is changed from:

- Bus A voltage is 1.00 pu

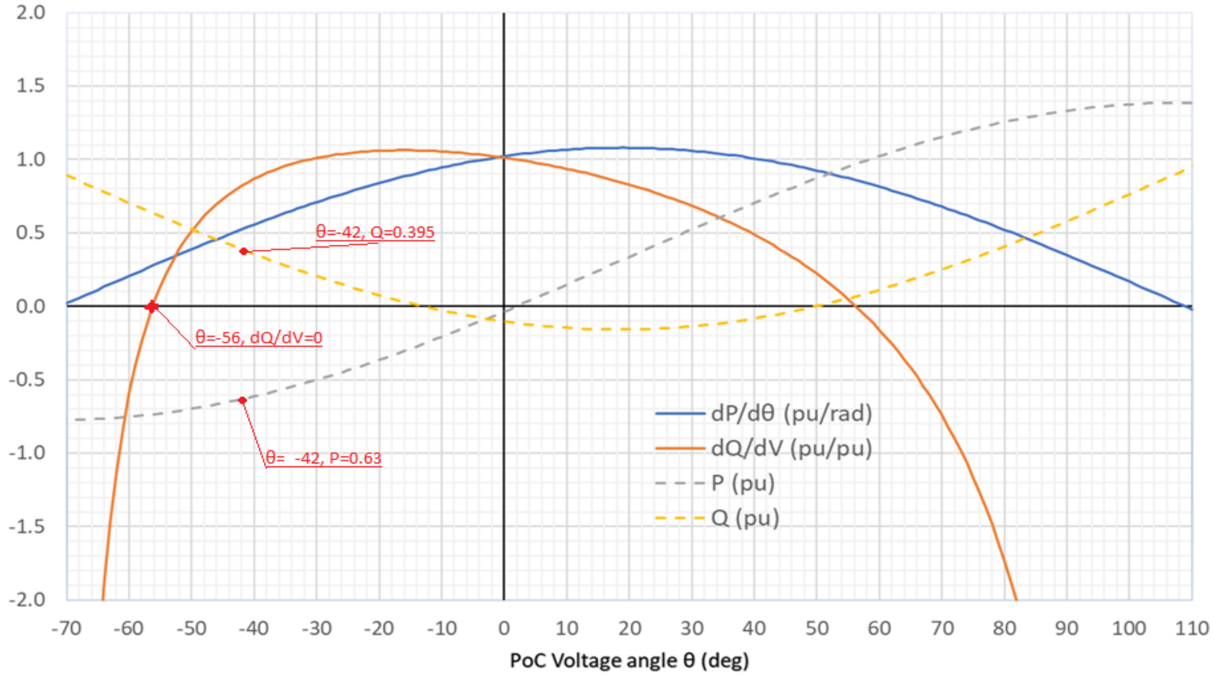
TO

- Bus A voltage is flexible, but must be no less than 0.90 pu, and the plant reactive power must be within ±0.395 pu

then the maximum active power that the plant can absorb is 0.63 pu (that is, active power cannot be more negative than -0.63 pu). This is at the operating point where θ is equal to -42°, as shown in Figure 5.

[17] NER S5.2.5.1

Figure 5 Static stability check on a 2-bus system (SCR = 1.2, X/R = 3, Vth = 1.0 pu, and V = 0.9 pu)



2.3 Proposed criteria in determining static stability limit for plant absorbing active power

Based on the investigation performed, the proposed criteria for determining the active power static stability limit for a plant absorbing active power are:

1. The infinite bus voltage operates as close as possible to 1.00 pu and must not exceed 1.05 pu
2. For a two-bus grid, the voltage angular reserve is no less than 10° for both $\partial P/\partial \theta > 0$ and $\partial Q/\partial V > 0$[18]
3. Plant reactive power is within ±0.395 pu[19] in steady state
4. Plant steady state post-disturbance voltage must be 0.90 pu or higher, and as close to 1.00 pu as possible.

In addition to the static stability limit, the connecting plant is also subject to a dynamic stability limit, thermal limit, and other control limits.

[18] 10° angular reserve is considered typical based on SCR of 1.2 and X/R of 3, but can be reduced until 0° provided the stability is maintained.

[19] Unless the reactive power range is otherwise agreed with the connecting NSP.

2.4 Sensitivity analysis for different SCR and X/R ratios

2.4.1 Plant active power absorption limit on a grid with SCR = 1.2

By applying the criteria proposed in Section 2.3, the active power absorption limit of a plant in a two-bus grid is presented by the blue curve in Figure 6. As a comparison, the orange curve in Figure 6 shows the active power limit when the plant reactive power is unlimited and hence the plant voltage can be kept at 1.00 pu.

Figure 6 Plant active power absorption limit on SCR 1.2 grid of different X/R ratios

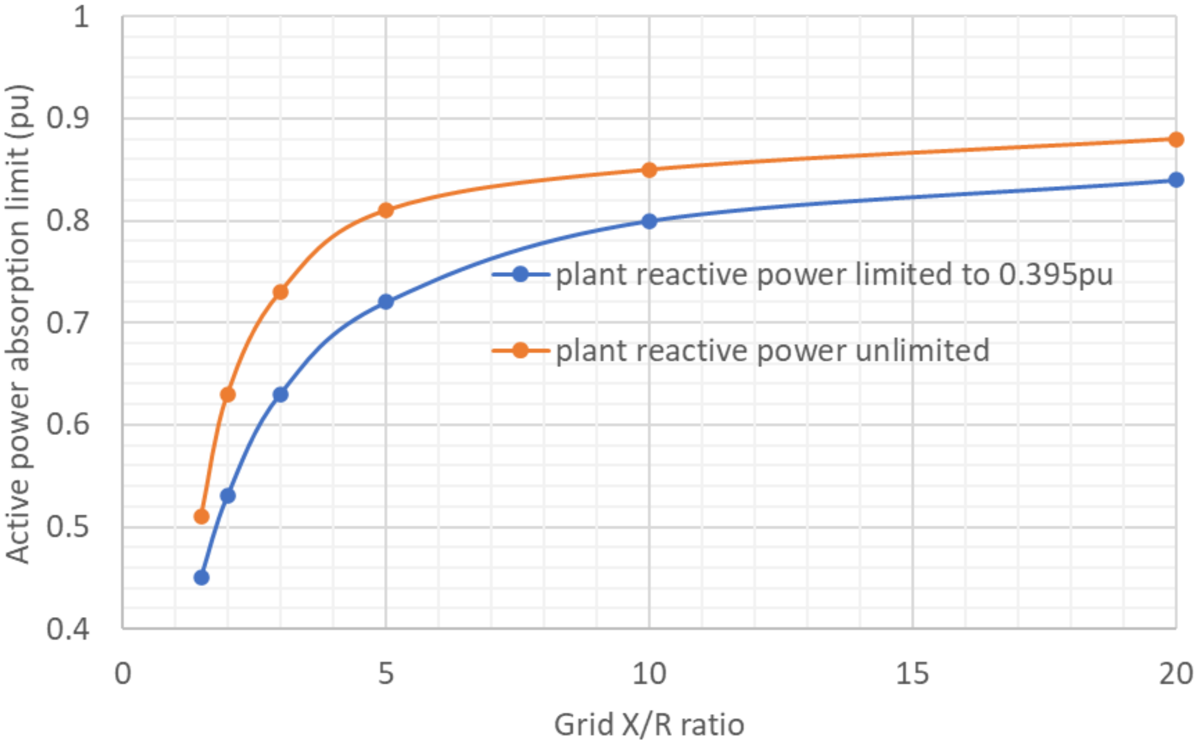


Figure 6 shows:

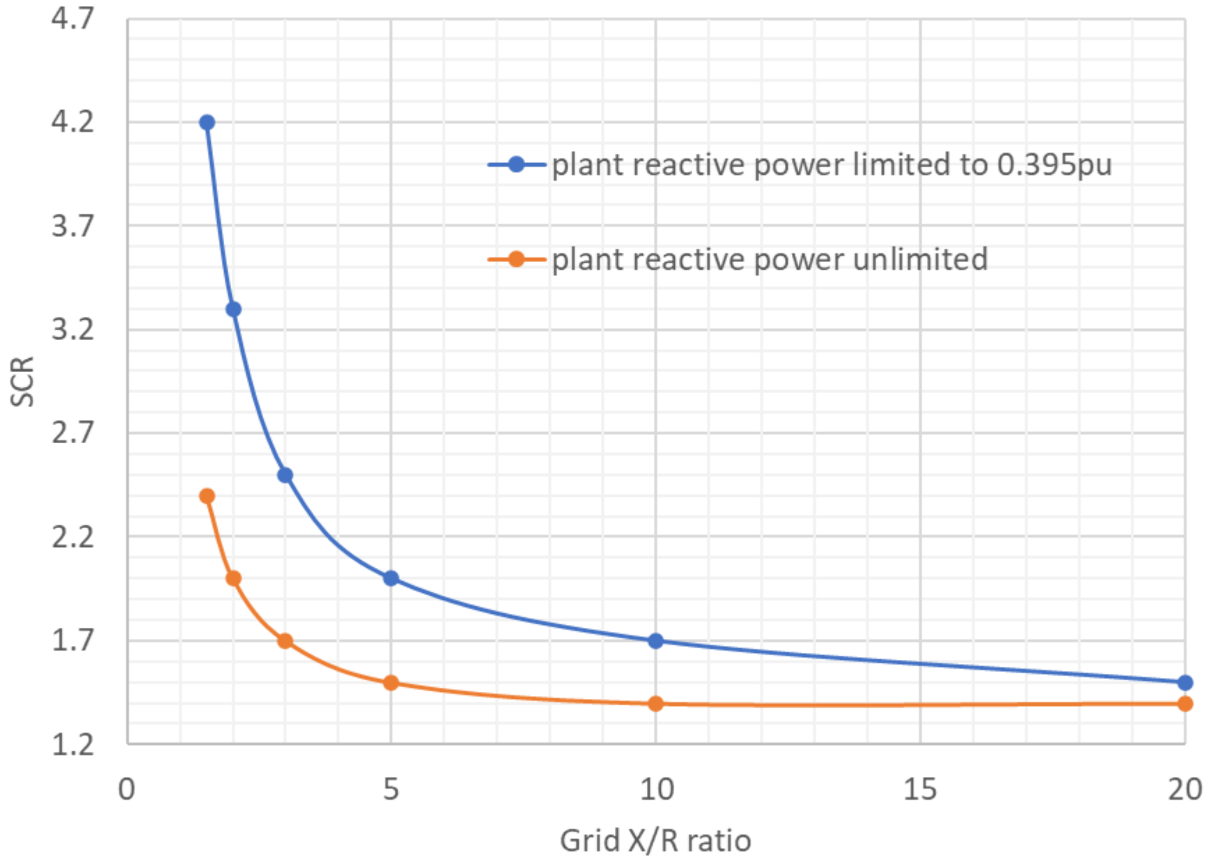
- The active power absorption limit is sensitive to the X/R ratio of the grid
- A lower X/R ratio results in a reduced active power absorption limit.

The lower X/R ratio results in a lower active power absorption limit because, for a given SCR, the active power losses increase as the X/R ratio decreases. Hence, for the same amount of active power sent out from the infinite bus, the amount of active power measured at the plant is lower when the X/R ratio is lower.

2.4.2 Minimum SCR for plant absorbing 1.0 pu active power

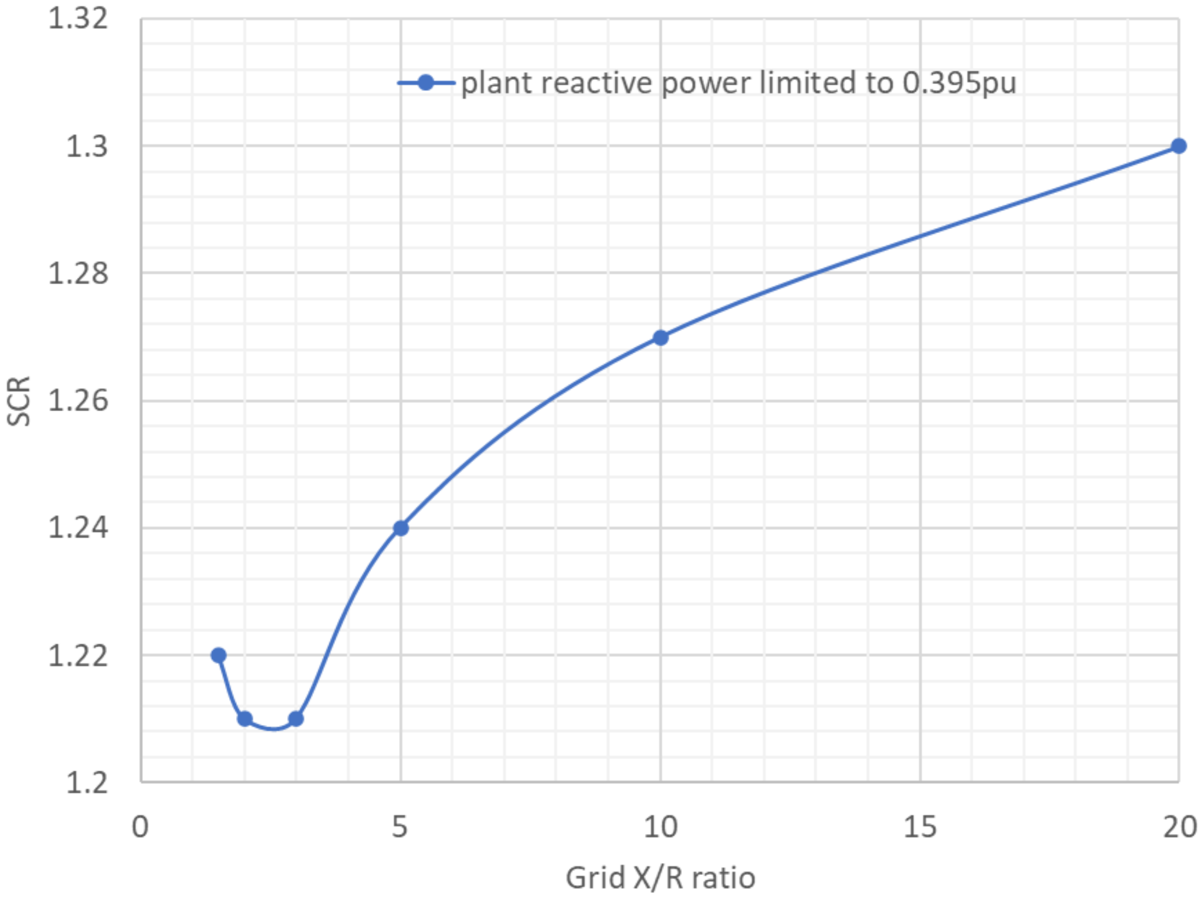
To meet the criteria specified in Section 2.3, when the plant active power absorption is 1.00 pu, the minimum SCR of the grid for X/R ratios between 1.5 and 20 is represented by the blue curve in Figure 7. It can be observed that the minimum SCR is sensitive to the X/R ratio. For example, the minimum SCR is 1.7 when the X/R ratio is 10, but the minimum SCR increases to 2.5 for an X/R ratio of 3. The orange curve in Figure 7 shows the minimum SCR when the plant reactive power is unlimited (and hence the plant voltage can be kept at 1.00 pu).

Figure 7 Minimum SCR requirement for a plant absorbing 1.00 pu active power on different grid X/R ratios



For comparison, Figure 8 presents the minimum SCR requirement for a plant in generation mode that satisfies the criteria in Section 2.3. It shows that for generation mode, the minimum SCR is not as sensitive to the X/R ratio and is between 1.2 and 1.3. The turning point shown in Figure 8, approximately at an X/R ratio of 2.5, is due to the changes between the active and reactive power losses. As the grid becomes more resistive, the active power losses increase together with the minimum SCR at low X/R conditions.

Figure 8 Minimum SCR requirement for a plant generating 1.00 pu active power on different grid X/R ratios



2.5 Impact of SCR and X/R ratio on active power absorption transfer limit

As demonstrated in Sections 2.4.1 and 2.4.2, the plant active power absorption limit that meets the criteria specified in Section 2.3 is sensitive to both the grid SCR and X/R ratio. Table 1 summarises the calculation result of the active power absorption limits for different SCR and X/R ratios.

Table 1 Two-dimensional linear interpolation table for determining plant active power absorption limit according to grid SCR and X/R ratio

	Plant active power absorption limit (pu)					
X/R ratio	**SCR=1.2**	**SCR=1.5**	**SCR=1.7**	**SCR=2.0**	**SCR=2.5**	**SCR=3.0**
1.5	0.45	0.53	0.57	0.62	0.72	0.80
2	0.53	0.61	0.66	0.73	0.84	0.94
3	0.63	0.73	0.79	0.88	1.00	1.00
5	0.72	0.85	0.92	1.00	1.00	1.00
10	0.80	0.95	1.00	1.00	1.00	1.00
20	0.84	1.00	1.00	1.00	1.00	1.00

For SCR or X/R ratios that are not shown in Table 1, a two-dimensional linear interpolation lookup method can be used to find the active power absorption limit.

As shown in Table 1, by reducing the plant's active power absorption, the two-bus system is statically stable and the power transfer limits are not violated.

3 Dynamic simulations validation

The static limits presented in Section 2 impose guaranteed limits for stable plant response, assuming ideal plant dynamic voltage control at the connection point. The dynamic stability can be different from the static limit, but the static limit is still the main consideration in the active power absorption.

This section is to provide examples of dynamic stability studies (undertaken in a PSCAD™ SMIB network) for a typical design of an IBR plant considering its internal impedance and voltage control strategy. The plant is assumed to have ±100 MW of capacity at the connection point, with an internal impedance of 18% on 100 MVA base with an option to select grid-following or grid-forming modes.

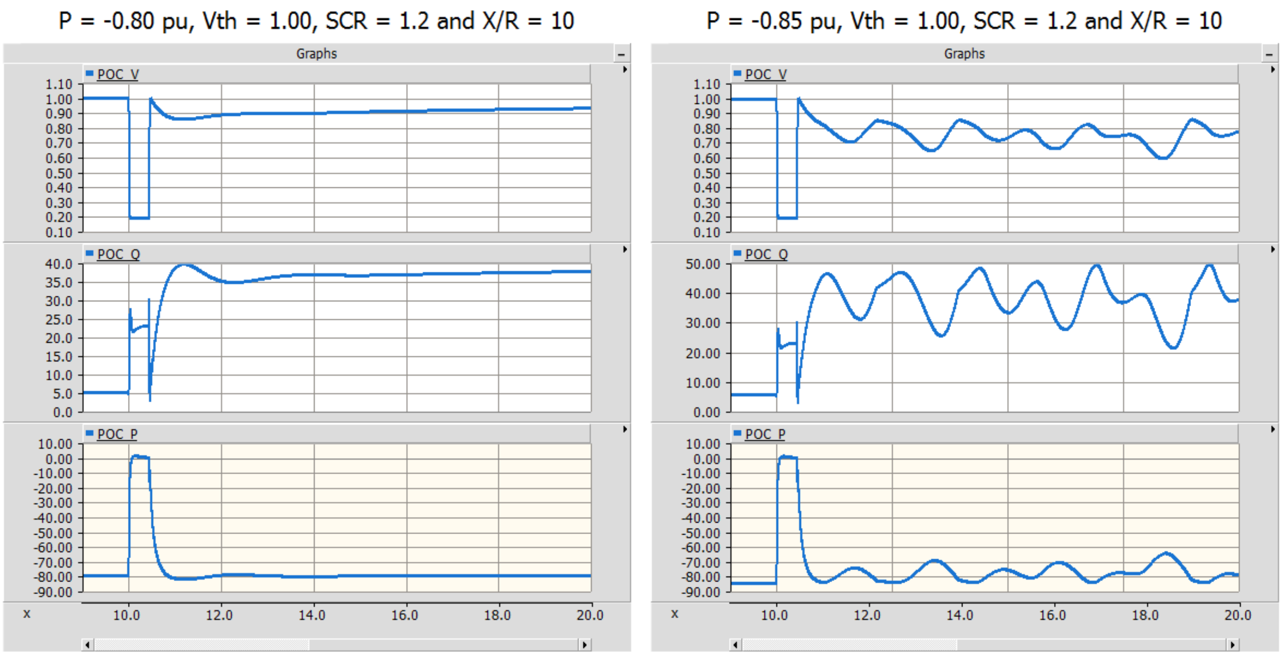
The PSCAD™ study analyses the dynamic stability of the plant for different control modes, active power levels, grid X/R ratios, and infinite bus voltages.

3.1 Grid-following and grid-forming control mode comparison during active power absorption

From a static stability perspective, the technology or the control mode of the plant has no particular significance. To assess this aspect and to validate the power transfer limits proposed in Table 1, PSCAD™ simulations are performed using both grid-following and grid-forming modes.

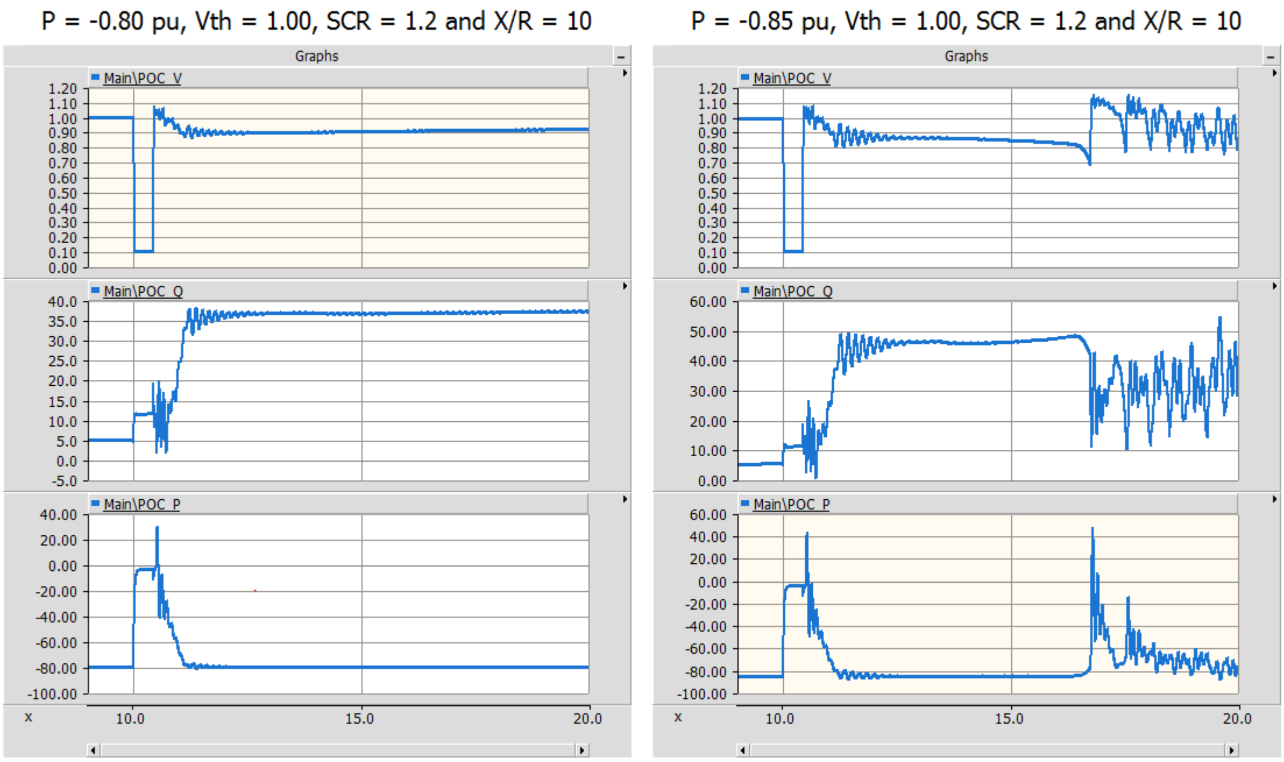
Figure 9 shows an example of successful and unsuccessful ride-through at SCR of 1.2 and X/R ratio of 10 for a BESS operating in grid-forming mode. The plant hits its power absorption limits above 0.8 pu active power condition. The simulation results are consistent with Table 1, which defines the plant active power absorption limit at 0.8 pu for an SCR of 1.2 and X/R ratio of 10.

Figure 9 Successful and unsuccessful ride-through examples at SCR = 1.2 and X/R = 10 (GFM)



To demonstrate that the static stability issues are independent of the control mode, the simulation has been repeated with the same test conditions. The results are shown in Figure 10for the BESS in grid-following mode. Similarly to the grid-forming mode test case presented in Figure 9, the power transfer limits are violated above 0.8 pu active power absorption.

Figure 10 Successful and unsuccessful ride-through examples at SCR = 1.2 and X/R = 10 (GFL)



While the static stability limits apply uniformly to the different control modes, there are differences in the BESS's dynamic stability for grid-following and grid-forming technology. Comparison of the dynamic stability of grid-forming and grid-following technologies is beyond the intent of this technical note.

3.2 Sensitivity on active power absorption level

To validate the static stability limits summarised in Table 1, additional X/R ratio conditions are analysed. Figures 11 and 12 provide examples of successful and unsuccessful ride-through events using grid-following control mode for an SCR of 1.2 and X/R ratio of 3. Reducing the X/R ratio from 10 to 3 creates a more onerous condition for the plant to ride through. According to Table 1, the plant active power absorption limit is 0.63 pu, when operating at an X/R ratio of 3 and SCR of 1.2.

Figure 12 shows that unstable behaviour occurs at 0.7 pu charging active power. Although the system remains stable in the case with charging active power of 0.65 pu, the plant is operating outside of its normal operating conditions at the connection point, with voltage less than 0.90 pu after the fault event. This does not meet the post-fault voltage criteria defined in Section 2.3, even when the plant total capacitive output of 39.5 MVAr is released. Consequently, the simulation verifies the 0.63 pu static stability limit indicated in Table 1.

Figure 11 Successful ride-through examples at SCR = 1.2 and X/R = 3

P = -0.60 pu, Vth = 1.00, SCR = 1.2 and X/R = 3 | P = -0.63 pu, Vth = 1.00, SCR = 1.2 and X/R = 3

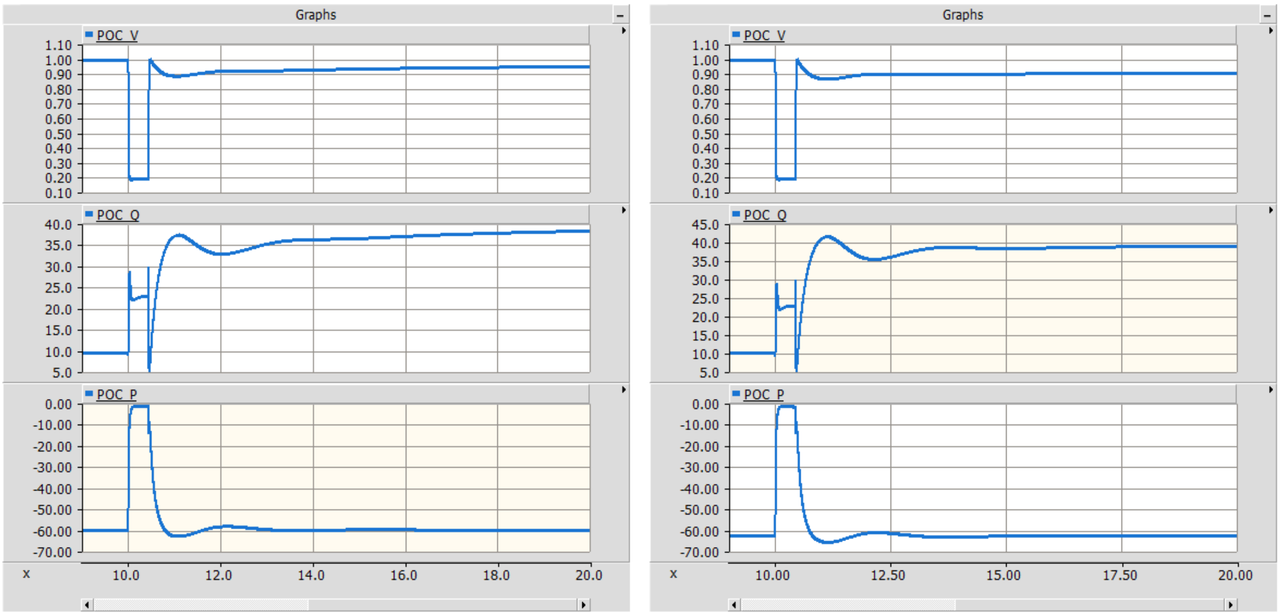
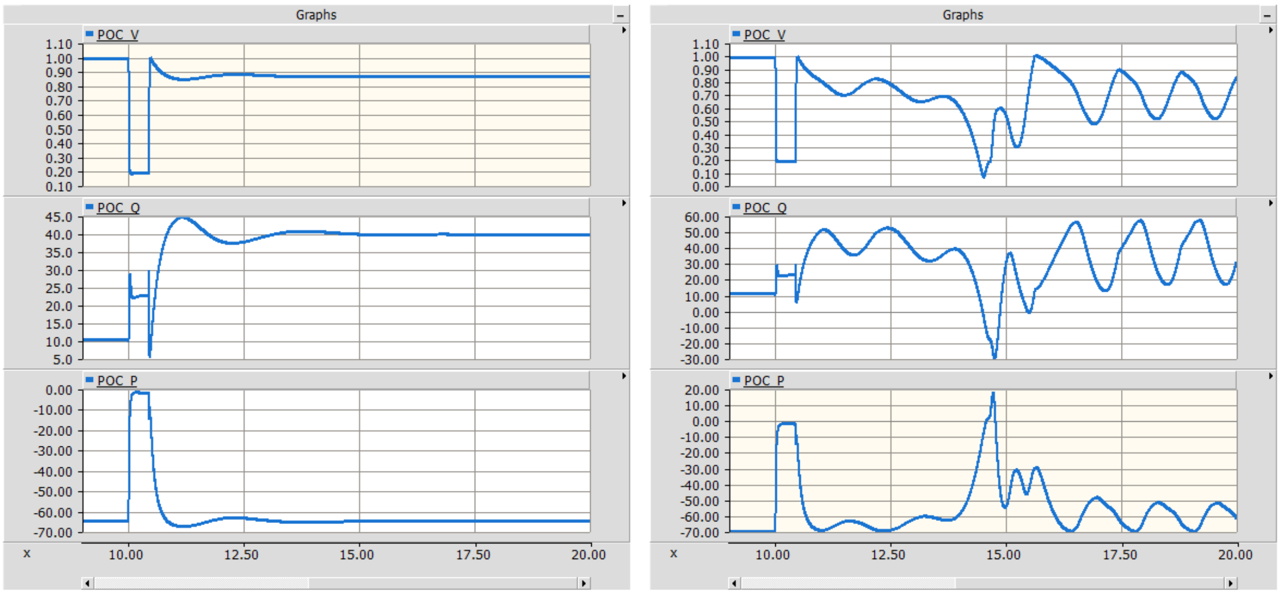


Figure 12 Unsuccessful ride-through examples at SCR = 1.2 and X/R = 3

P = -0.65 pu, Vth = 1.00, SCR = 1.2 and X/R = 3 | P = -0.70 pu, Vth = 1.00, SCR = 1.2 and X/R = 3



3.3 Sensitivity on infinity bus voltage

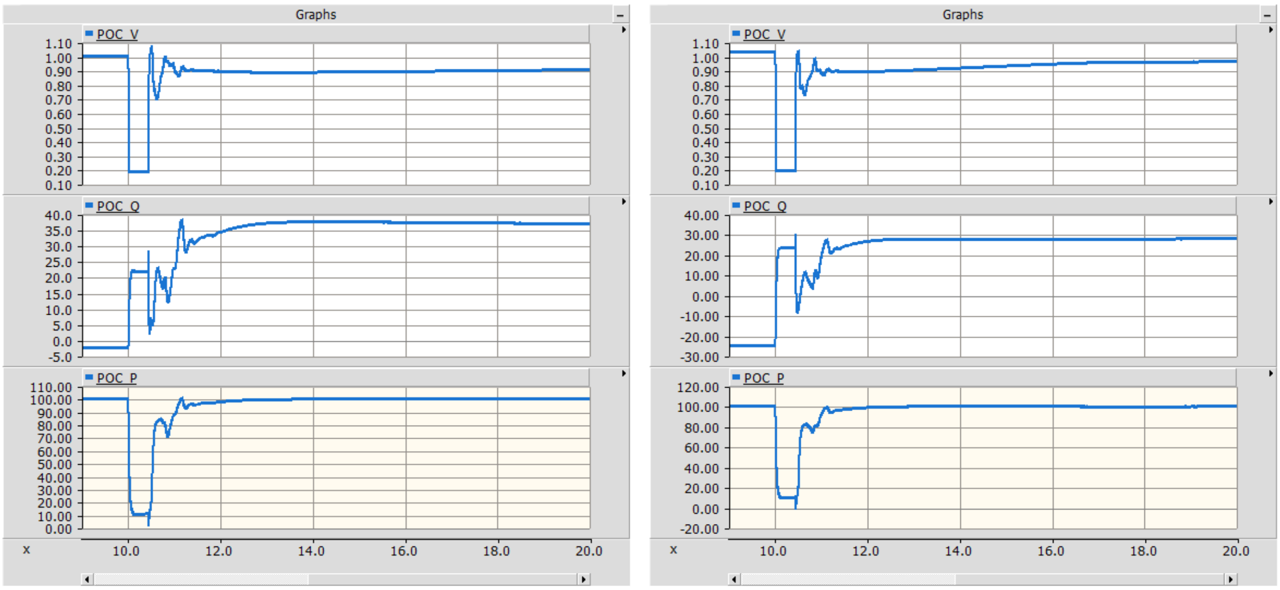
Setting the infinite bus voltage has a direct impact on the static stability. In general, higher voltages extend the transfer capability. To demonstrate this, different infinity bus voltages have been studied.

Figure 13 presents a successful ride-through event with the inverters operating in grid-following mode. This example demonstrates the influence of the infinity bus voltage (Vth) in the initial and post-fault conditions. The initial voltage and reactive power measured at the connection point will be determined by the selected voltage source setpoint and the plant's overall voltage control strategy. The selection of a 1.05 pu infinity bus voltage instead of a 1.00 pu creates a more favourable condition to ride through the fault, with increased reactive power support provided by the plant.

Figure 13 Successful ride-through examples at SCR = 1.2 and different Vth

P = 1.00 pu, Vth = 1.00, SCR = 1.2 and X/R = 10

P = 1.00 pu, Vth = 1.05, SCR = 1.2 and X/R = 10



4 Recommendations

This technical note examines the fundamentals of the theory which impacts the limits of power transfer capability in the Withstand SCR tests reflected in the SSIAG. Static analysis alongside dynamic simulations are used to illustrate the limitations of the current SSIAG methodology. As it stands, the guideline requires connecting plant that absorb active power from the network (IBL, hybrid plants and BESS) to undertake tests which result in a breach of power transfer limits. This represents a gap in the current methodology that is impacting some projects in the connections process and has resulted in inconsistent approaches being adopted to overcome the issue.

AEMO proposes clarifications and adjustments to the Withstand SCR test methodology for both generation and load (active power absorption) modes of operation based on the results presented in the previous sections. The proposed clarifications and adjustments in methodology address the limitations inherent in the current methodology when applied to hybrid plants and BESS. In the case of IBL, AEMO considers that the issue requires further investigation and should be addressed in a separate technical note.

4.1 All plant withstand SCR tests

The setting of the source voltage is not specified in Tables 2, 3, and 4 in Appendix B of the SSIAG. The assessment result is highly sensitive to this setting due to the plant's available reactive power to support the grid after the fault clearance. This is demonstrated by the simulation results provided in Section 3.3.

Due to the sensitivity of the minimum SCR to changes in the X/R ratio, as presented in Figure 8, and the stability coefficient being fixed at the value of 1.2, the plant violates the static stability limits even in generation mode when the infinite bus voltage is set to 1.00 pu. To avoid this situation and to provide a consistent approach, **AEMO proposes to set the infinite bus voltage in the range between 1.00 pu and 1.05 pu**. **The assessment should commence with an infinite bus voltage of 1.00 pu applied. The infinite bus voltage should be gradually increased by 0.01 pu steps, if required, but should not exceed 1.05 pu. With the infinite bus voltage set within the proposed range, the plant steady state reactive power must remain within ±0.395 pu unless otherwise agreed with the connecting NSP.**

4.2 Withstand SCR Tests applied to bi-directional plant operating in active power absorption mode

When Withstand SCR is assessed for a variable speed pumped hydro or BESS plant (or a hybrid plant containing BESS) operating in active power absorption mode, the test cases specified in Tables 2, 3, and 4 in the SSIAG must be adjusted. This is required to reflect the static stability limits that apply during active power absorption mode, as summarised in Table 1, when considering the grid SCR and X/R ratio. The ΔAFL calculation specified in the SSIAG[20] is not proposed to be changed.

[20] SSIAG 3.4.2

To set the plant's active power absorption limit the following needs to be defined:

1. Let P_{Rated} be the plant rated active power at the connection point. P_{Rated} is the SCR base and the per unit base
2. Let $SCR_{Withstand}$ be determined in plant generation mode
3. Let P_{LIMIT} (a positive value) be the active absorption limit looked-up according to Table 1
4. Let P_{ABSORB} (a positive value) be the designed absorbing active power capacity at the connection point
5. Let $P_{REVERSE}$ (a negative value) be defined as -1 times the minimum of P_{LIMIT} and P_{ABSORB}
6. For a hybrid plant containing BESS (for only BESS plant configuration P_{GEN} is equal to zero):
   - Let P_{BESS} be the active power of BESS (a negative value)
   - Let P_{GEN} be the sum of the generation of all other resources (zero or a positive value)
   - Let P_{LOSSES} be the active power losses within the plant (a positive value).

For the Withstand SCR tests the following conditions are required:

1. The reactive power at the connection point is flexible but must be within ±0.395 pu unless otherwise agreed with the connecting NSP
2. The infinity bus voltage must be set between 1.00 pu and 1.05 pu, but as close as possible to 1.00 pu, according to recommendation provided in Section 4.1
3. Plant steady state post-disturbance voltage must be 0.90 pu or higher, and as close to 1.00 pu as possible
4. For a hybrid plant containing BESS, various combinations of the active power output of different resources (P_{BESS} and P_{GEN}) need to be studied. In both minimum and maximum P_{GEN} conditions, the $P_{BESS} + P_{GEN} – P_{LOSSES} = P_{REVERSE}$ equation needs to be met.

If the withstand SCR test cases with conditions detailed above show unsatisfactory results (with acceptance criteria defined in the SSIAG[21]), P_{ABSORB} is required to be decreased with the effect to change P_{BESS} and P_{GEN} until all withstand SCR tests are satisfied. The $P_{REVERSE}$ obtained through this process is the plant's active power absorption limit[22]. An example to define the absorption limit of a hybrid plant containing BESS is provided below.

[21] SSIAG 7.4.4

[22] Subject to thermal limit, full assessment or stability assessment, and negotiation between NSP and the connection applicant, the actual active power absorption limit may be different from this value.

Example

Grid equivalence assumptions: SCR = 1.7 and X/R = 3.

The proposed assessment methodology:

1. P_{LIMIT} = 0.79 pu is selected from Table 1
1. P_{ABSORB} is assumed to be 1.00 pu
2. Based on P_{LIMIT} and P_{ABSORB}, $P_{REVERSE}$ can be calculated as the negative minimum value of P_{LIMIT} and P_{ABSORB} that is equal to -0.79 pu
3. To define P_{BESS} for minimum and maximum P_{GEN} the $P_{BESS} + P_{GEN} – P_{LOSSES} = P_{REVERSE}$ equation needs to be satisfied:
   a. If possible minimum P_{GEN} = 0.00 pu and related P_{LOSSES} = 0.01 pu, then P_{BESS} = -0.78 pu. The equation looks like:

      $P_{BESS} + P_{GEN} – P_{LOSSES} = - 0.78 + 0.00 – 0.01 = -0.79 = P_{REVERSE}$

   b. If possible maximum P_{GEN} is assumed to be 0.23 pu and related P_{LOSSES} = 0.02 pu then P_{BESS} is calculated to be – 1.00 pu. The equation changes to the following:

      $P_{BESS} + P_{GEN} – P_{LOSSES} = - 1.00 + 0.23 – 0.02 = -0.79 = P_{REVERSE}$

4. Considering the minimum and maximum generation, two scenarios need to be studied for the withstand SCR tests:
   a. P_{BESS} = - 0.78 pu when minimum P_{GEN} = 0.00 pu, and
   b. P_{BESS} = - 1.00 pu when maximum P_{GEN} = 0.23 pu
5. If the plant during the withstand SCR tests does not meet satisfactory results provided in section 2.3, change P_{ABSORB} to a less negative value (e.g., new P_{ABSORB} = -0.77 pu) and recalculate P_{BESS} for minimum and maximum P_{GEN}
6. Reduce P_{ABSORB} until the withstand SCR tests show satisfactory results. Confirm the plant thermal limits are not violated. The obtained P_{ABSORB} is the proposed plant active power absorption limit.

4.3 Tests applied to inverter-based load

Power transfer issues like those discussed in the previous sections are also expected for a plant considered as an IBL. **AEMO suggests that these be addressed in a separate technical note** for the following reasons:

- The static stability requirement on minimum SCR for a plant is highly sensitive to the plant reactive power capability, as well as the grid X/R ratio that the plant is connected to
- IBL have only one direction of active power flow and less flexibility in reducing load levels when compared to BESS
- Many IBL are thyristor or diode-based converters where the controls are more inferior to a grid-scale IBR
- IBL may need reactive power compensation for reasons not limited to NER S5.2.5.1 (for example, commutation or harmonics)
- Little experience has been gained in the National Electricity Market (NEM) on the design, connection, and operation of IBL.

5 Other matters to be considered

In addition to the recommendations outlined in Section 4, it is important to highlight that since the Withstand SCR test is conducted in a SMIB, PSCAD^{TM} simulations showing stable performance are possible even where the angle stability limit is reached (noting this situation would incur in $\partial V/\partial Q < 0$ for the voltage stability criteria at some buses including the connection point). The displacement of approximately 90° between voltage source and terminals is not relevant on the wide area network and tests which occur in such conditions can be disregarded. Wind farms with large reticulation impedances are prone to this issue.